

# Beam-beam design criteria for LHC

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## Abstract

The nominal parameters of the LHC were chosen such as to provide simultaneously a luminosity of  $10^{34} \text{cm}^{-2} \text{s}^{-1}$  in two diametrically opposite experiments, around  $10^{32} \text{cm}^{-2} \text{s}^{-1}$  in a third experiment and around  $10^{30} \text{cm}^{-2} \text{s}^{-1}$  in a fourth one. Considering experience in previous colliders, it was decided to limit the total beam-beam tune spread (between 0 and 6 sigma amplitude particles) to 0.01. However, the machine components were designed with just enough safety margin to allow operation with a beam intensity (and a resulting beam-beam tune spread) 1.5 times larger than nominal. The long range interactions are reduced by making the beams cross at an angle of  $\pm 150 \mu\text{rad}$ , but still dominate the dynamics of large amplitude particles and of the coherent modes. Synchrotron satellites of the  $13^{\text{th}}$  order resonance which cross the beam footprint, are excited by the main interaction in presence of crossing angle.

## 1 INTRODUCTION

In order to compensate for the small cross sections of hard collisions between the constituents of the protons in the TeV range, the LHC has to operate at a high luminosity, hence at the largest possible beam-beam parameter. Experience with previous hadron colliders, essentially the CERN *SPPS* and the Fermilab Tevatron, has shown that the maximum tolerable beam-beam tune spread is in the range 0.015 to 0.02. However the LHC differs in many respects from the proton-antiproton colliders: it has many more bunches, and both beams have the same intensity. In the first section we introduce the main features of the LHC relevant to beam-beam questions. Then we summarize the experience of previous machines, and present the assumptions which have been made to design the LHC. Finally, we highlight a few unresolved problems concerning beam-beam in the LHC.

## 2 FEATURES OF THE LHC

### 2.1 Luminosity

In a hadron collider the most convenient form in which to express luminosity is:

$$L = \frac{\gamma}{4\pi e \beta^*} \left[ \frac{N}{\varepsilon_n} \right] [N k f e] \quad (1)$$

where  $\gamma$  is the energy divided by the energy at rest,  $e$  is the unit charge,  $\beta^*$  is the value of the betatron function at the collision point,  $N$  the number of particles in each of the  $k$  bunches,  $f$  the revolution frequency and  $\varepsilon_n = \sigma^2 \gamma / \beta$

the normalized transverse emittance of the beam assumed to be round. The first bracket is the transverse particle density. It is proportional to the beam-beam parameter  $\xi = r_p N / 4\pi \varepsilon_n$ , with  $r_p$  the particle classical radius, and also to the direct space-charge detuning in the injectors. The second bracket is the beam current. This quantity is limited by many different phenomena like instabilities, beam losses, loading of the cryogenic system. Whereas the beam density determines the strength of the head-on (or quasi head-on in the LHC) interaction, the total beam intensity is linked to the parasitic long-range interactions.

### 2.2 The interaction points

In the LHC [1] the beams collide in 4 interaction points (IP), as seen on Fig. 1.

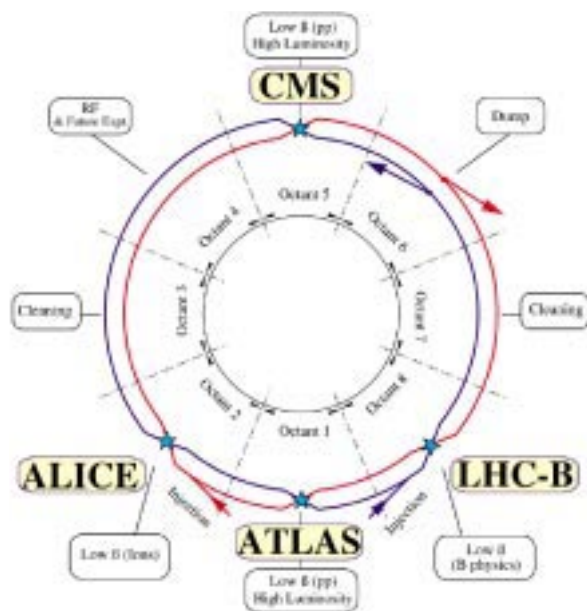


Figure 1: LHC layout

In points 1 and 5 (respectively ATLAS and CMS) a luminosity of  $10^{34} \text{cm}^{-2} \text{s}^{-1}$  is required, and to achieve this the betatron function is reduced in both planes to  $\beta^* = 0.5 \text{ m}$ . The resulting large divergence of the beams in these locations make it difficult to separate the two beams sufficiently to avoid parasitic beam-beam interactions. With the nominal crossing angle of  $\pm 150 \mu\text{rad}$  the average separation in the 15 parasitic collision places on either side of the IP is about  $9\sigma$ . The orbit excursion reaches 6 mm in the low beta quadrupole triplets, where the betatron function

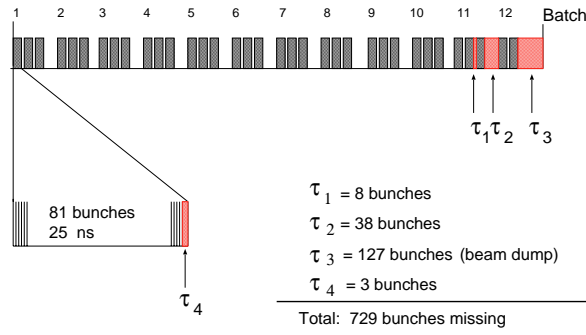


Figure 2: LHC bunch disposition

assumes very large values (beta max= 4.7 km). As a result, the stability of large amplitude particles is sensitive to magnetic errors in the triplet, in addition to parasitic long range beam-beam effects. In IP8 (LHC-B) the required luminosity is around  $10^{32} \text{cm}^{-2} \text{s}^{-1}$  and  $\beta^* = 50 \text{ m}$ . It is easier to separate the beams. In IP2 the heavy ions experiment ALICE intends to observe proton-proton collisions with a luminosity around  $10^{30} \text{cm}^{-2} \text{s}^{-1}$ . This cannot be provided during high intensity operation through head-on collisions. Instead we foresee to separate the beams at this IP by about 4 to 5  $\sigma$  to provide halo collisions.

### 2.3 The bunch schedule

The 2835 bunches are distributed along the ring as shown in Fig. 2. The different holes are necessary to accommodate the rise times of the different injection kickers in the LHC and its injectors, and that of the beam abort kicker. An important consequence of the presence of these holes is that many bunches meet no partner in parasitic collision places. There are many classes of these "PACMAN" bunches, depending on the number of their missing encounters. Each class has a different long-range interaction, in particular a different "tune footprint".

By injecting symmetrically  $n$  equal batches in the LHC (with  $n$  a multiple of 4) one would ensure that all bunches find a partner in all of the 8 possible interaction points. However we need only one large hole for the abort kicker, and this breaks the symmetry. In addition, one of the interaction points (IP8) has been displaced longitudinally to save on civil engineering. For these two reasons there are bunches ("SUPERPACMAN") which have no partner in IP8 and IP2. All bunches collide in IP1 and IP5, in the high luminosity experiments.

### 2.4 Footprints

The beam projection on the tunes plane (the "tune footprint") was an important ingredient in the interpretation of observations in previous hadron colliders. In the LHC the tune footprint is modified by the long range interactions [2], as illustrated in Fig. 3. Here the crossing angle is reduced to  $\pm 100 \mu\text{rad}$  (2/3 of the nominal value) which makes

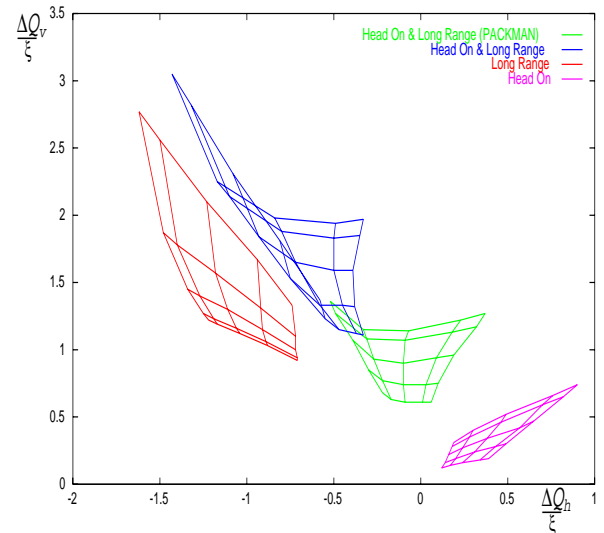


Figure 3: LHC tune footprints, for 1 interaction and a crossing angle  $\pm 100 \mu\text{rad}$

the effect more visible. When the long range interactions are included, the footprint is displaced (this can be compensated with tuning quadrupoles) and enlarged. An even more important effect is that now PACMAN bunches are displaced with respect to normal bunches. This increases the area which has to be accommodated in between high order resonances and therefore reduces potential performance. We plan to minimize this effect in the LHC by making the beams cross in the horizontal plane in one of the high luminosity insertions, and in the vertical plane in the other. The resulting footprint is more symmetrical and the enlargement due to PACMAN bunches is much reduced, as can be seen in Fig. 4.

## 3 ASSUMPTIONS MADE TO DESIGN LHC

### 3.1 Experience from previous colliders

Fig. 5 summarizes the data which were available at the beginning of the design period of the LHC, concerning the  $S\bar{P}PS$  and the Tevatron.[3] The  $S\bar{P}PS$  had operated with 6 bunches per beam separated by electrostatic deflectors in 9 out of 12 encounters. This left 3 interaction points, two of them used by experiments in low beta insertions with zero dispersion at the crossing point, the third occurring in the arc in between with a non zero dispersion. The beam-beam parameter  $\xi$  was about 0.006 for antiprotons, about 3 times less for protons. Both beams had about equal transverse emittances. Fig. 5.5 shows that the antiproton footprint was lodged between the 3<sup>rd</sup> order resonance and the 10<sup>th</sup> order (beam-beam excited) resonances. Incursion of the footprint in the area of the 10<sup>th</sup> order resonances produced an unacceptable reduction of the antiproton beam lifetime. The large amplitude particles (in the wide part of the footprint)

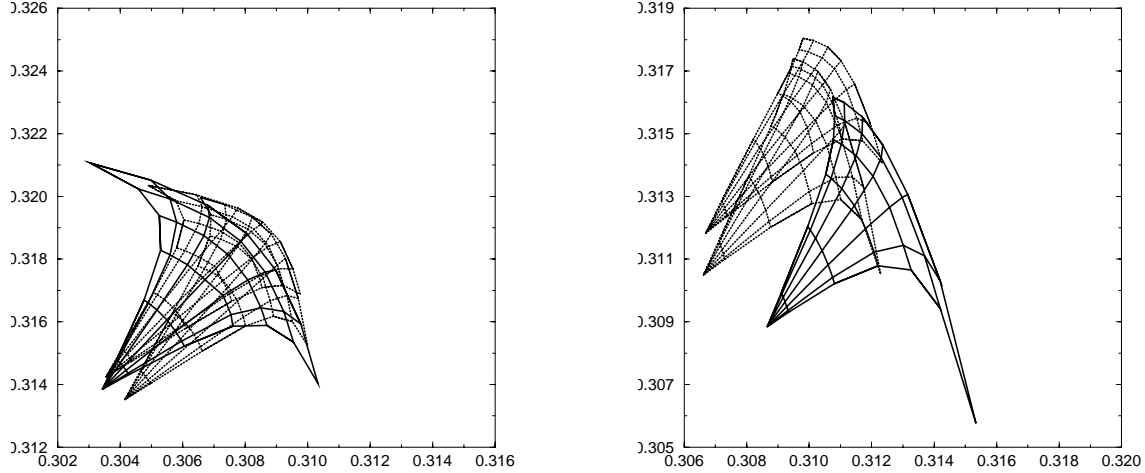


Figure 4: LHC nominal tune footprint for vertical-horizontal (left) and horizontal-horizontal crossings (right).

straddled resonances of order 13 and 16. Scanning specially prepared beams across the web of these resonances proved that they were indeed responsible for slow amplitude increase and particle loss. From these experiments it was inferred that the difference in beam lifetime observed between single beams and colliding beams (about 100 h in the first case, and 10 to 20 h in the second) was due to these resonances. Tune modulation due to synchrotron motion or power supply ripple was invoked to explain the phenomenon.

The Tevatron had operated with 6 bunches per beam and no separators, therefore with 12 collision points. The total beam-beam tune shift was larger than in the *SPPS*, but the beam-beam parameter  $\xi$  was about 3 times smaller. The protons had a larger emittance than the antiprotons. The tune footprint was lodged between 5<sup>th</sup> order and 7<sup>th</sup> order resonances, both excited by the machine imperfections. It was not possible to approach the 5<sup>th</sup> order resonance closer than indicated by the dashed line in fig 5. The central antiprotons (upper part of the footprint) could straddle 7<sup>th</sup> order resonances, while the large amplitude antiprotons (in the wide part of the footprint) crossed the 12<sup>th</sup> order (beam-beam excited) resonances.

### 3.2 Recipe for LHC

From the experience in the *SPPS* and the Tevatron we infer that in hadron colliders the total tune footprint must be lodged in between resonances of order less than or equal to 12. The case of resonances of order 10 is clear from the *SPPS*. Whether resonances of order 12 can be tolerated or not is less evident; in the Tevatron large amplitude antiprotons crossed the 12<sup>th</sup> order resonances. However, observations reveal a depletion of the beam distribution in the vicinity of these resonances [4]. Here let us remark that in the Tevatron the antiprotons had a smaller emittance than the protons. We know from experience in the *SPPS* [5] as

well as from HERA[6] that this was a very favorable situation: even large amplitude antiprotons oscillated in the quasi linear part of the field of the larger proton beam; high order resonances were much less excited than in the case of equal emittances.

Fig.6 shows three locations where the calculated tune footprint of the LHC can be lodged. Case 1 (single beam tunes  $Q_H = .31$ ,  $Q_V = .32$ ) is the equivalent for protons (below the 1/2 integer) of the *SPPS* working point for antiprotons. Case 3 is close to the Tevatron working point, but avoids the 12<sup>th</sup> order resonances. Case 2 is another possible candidate. Each point is below a low order resonance excited by the machine imperfections, and above a high order resonance excited by beam-beam. Whether one is better than the other will depend essentially on the excitation of resonances by the magnetic errors in the low beta triplets. In all the three points the large amplitude particles cross the 13th order resonances. In the LHC synchrotron sidebands of these resonances are excited by beam-beam due to the crossing angle. Inspection of Fig. 6 shows that the total beam-beam tune shift which can be tolerated with the assumptions made above is  $\Delta Q = 0.01$ , and this is the value assumed in the LHC design. It corresponds to a luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ .

However, comparison of Figs. 5 and 6 shows that a better performance could possibly be obtained. As seen on Fig.5 the *SPPS* as well as the Tevatron operated very close to the diagonal of the tune plane, although not quite on it. Operating on the diagonal maximizes the free area between sum resonances, but requires a very good correction of the coupling resonance. The best compromise found empirically in the *SPPS*, the Tevatron and HERA is to operate with a tune difference of 0.005. In the LHC, we expect the coupling resonance to be more strongly excited than in the previous machines, owing to the larger size of the LHC and the magnet imperfections. We have therefore taken a larger

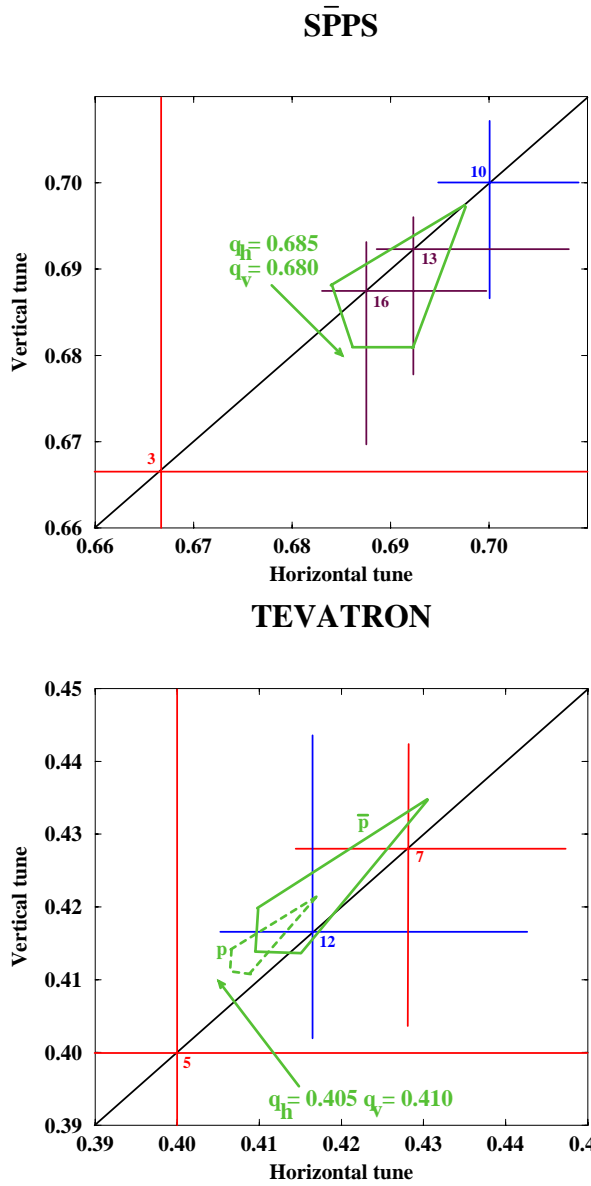


Figure 5: Working points of  $S\bar{P}PS$  and Tevatron

safety margin, and plan to operate with a tune difference of 0.01. If this could be reduced to 0.005 after careful adjustments, the tolerable beam-beam tune shift could increase to  $\Delta Q = 0.015$ , leading to a luminosity of  $2.3 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . This is called the "ultimate luminosity" and all systems of the machine and the injectors have safety margins just sufficient to allow this luminosity to be reached.

## 4 A FEW QUESTIONS SPECIFIC TO THE LHC

### 4.1 Triplet errors and long-range interactions

As we just saw, low order resonances excited by machine imperfections (essentially in the low beta quadrupoles) may restrict the tune area available for the beam-beam footprint.

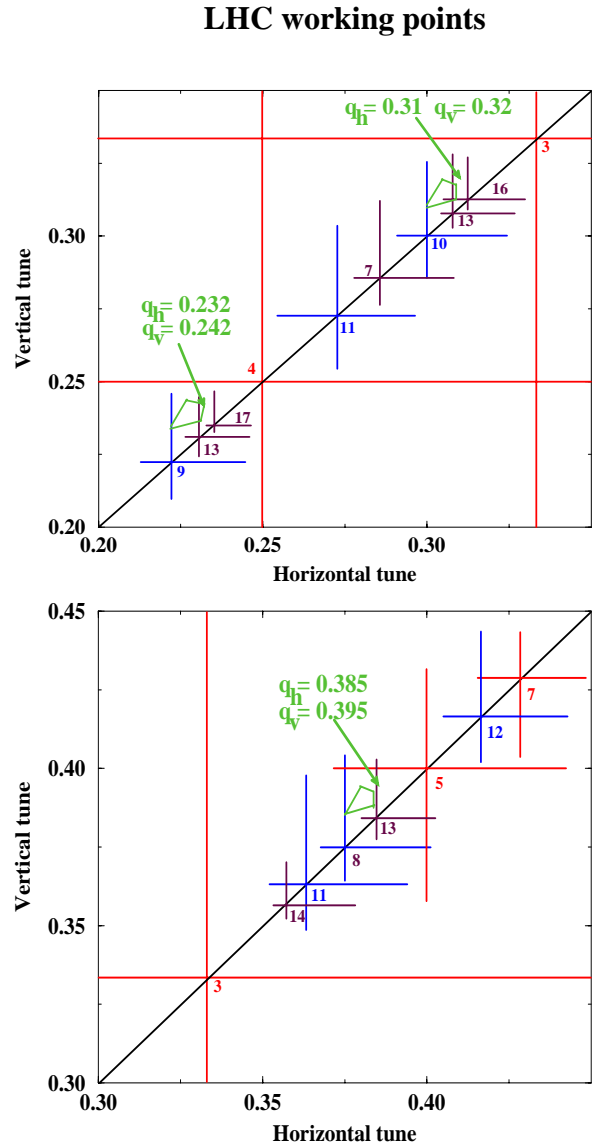


Figure 6: LHC Possible working points

Sensitivity to magnet errors is enhanced by the large beta values and also by the orbit excursions due to the crossing angle. A former study [7] using now obsolete tables of triplet errors showed that a maximum dynamic aperture was obtained with a crossing angle of  $\pm 150 \mu\text{rad}$ . For smaller values the dynamics of large amplitude particles was dominated by the long range beam-beam interactions, while for larger values the triplet errors prevailed. Since then a considerable effort has been made to reduce the triplet errors and to provide correction systems [8]. As a result in absence of beam-beam the dynamic aperture at  $10^5$  turns is larger than  $10\sigma$  and the tune shift induced by triplet errors is less than  $10^{-3}$  at  $6\sigma$ ; the beam-beam long range interactions are again the dominant factor. Much effort remains to be made in order to assess the stability of particles at an amplitude of about  $6\sigma$  in these conditions.

There is clearly an incentive to further increase the crossing angle. This would require shortening the bunches to minimize the resulting loss of luminosity.

## 4.2 Dynamics on the 13<sup>th</sup> order resonances

In the LHC large amplitude particles (at 5 to 6  $\sigma$ ) will cross 13<sup>th</sup> order resonances in all cases foreseen up to now. The excitation of synchrotron sidebands of these resonances by the beam-beam effect in presence of a crossing angle of  $\pm 150 \mu\text{rad}$  was studied in detail [9]. The strength of the first sideband is of the order of that obtained for the central resonance by displacing the beams with respect to each other by about 0.8  $\sigma$ . In the *SPPS* the effect of the 13<sup>th</sup> order resonances excited by partial beam separation was studied experimentally [10]: separating the beams clearly enhanced the background rates (due to particle losses in the tail of the distribution) in the experiments.

Little is known on the dynamics of large amplitude particles on such high order resonances. Simulations [10] showed that tune modulation might explain the slow diffusion rates observed in the *SPPS*. More work is required in this area.

## 4.3 Coherent modes

Beam-beam coherent effects (flip-flop, dipole oscillations) are often seen to limit the performance of electron-positron colliders. Such effects have not limited hadron colliders up to now, although the signature of coherent modes have been reported in the Tevatron [3]. It was stressed recently [11] that when beams of equal intensity and size collide, at least one coherent mode, the  $\pi$  mode in which the bunches oscillate with opposite phases, is shifted in frequency well outside the band of incoherent frequencies. In this case it is not damped by its interaction with the continuum (Landau damping). Since there is no other damping mechanism in hadron storage rings (in absence of active feedback), there is a potential danger of instability. An interesting finding [11] is that for sufficiently unequal beams this loss of Landau damping cannot occur. This may explain why no instabilities were observed in previous hadron colliders, which had unequal beams.

Instability can arise when the coherent mode coincides with a betatron resonance (usually a 1/2 integer resonance in lepton machines, but it could as well be a higher order resonance in hadron machines). Whereas this is a very serious problem in LEP (there are four interactions, the beam-beam parameter is large, and therefore the shift of the  $\pi$  mode is large), it should be easy to avoid such a coincidence in the LHC because of the small tune shifts involved.

Another cause of instability is multibunch wake fields. These are known to be important in the LHC owing to the large number of bunches of high intensity. A fraction of the many thousand multibunch modes of the system of two counterrotating beams coupled by the beam-beam effect will acquire an imaginary frequency shift from the wake

field interaction. If Landau-damping is suppressed for one of these, instability will be observed.

It is therefore important to better understand the dynamics of the collective modes in beam-beam coupled systems of bunches. In the LHC the situation is extremely complex because there are so many classes of bunches, each with different collision sequences. The long range interaction completely changes the picture, compared to the simple head-on interaction studied in [11].

## 5 CONCLUSIONS

Most of the beam-beam design criteria of the LHC have solid foundations in experience from previous colliders. However many features of the LHC are new and further work is required to understand possible limitations and optimize the operation of the machine.

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